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DOSE ATTENUATION FACTORS FOR CONCRETE SLAB SHIELDS COVERED WITH FALLOUT AS A FUNCTION OF TIME AFTER FISSION

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DOSE ATTENUATION FACTORS FOR CONCRETE SLAB SHIELDS COVERED WITH FALLOUT AS A FUNCTION OF TIME AFTER FISSION

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by

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OBJECT OF TASK

To improve existing knowledge of gamma and neutron-shielding properties of shelters, and where necessary, to verify experimentally the theoretical information developed in this field.

ABSTRACT

For radiation shielding, underground or buried fallout shelters have an important advantage over other types of shelters, because the attenuation of the radiation in such a shelter is primarily a function of the thickness of the material in the roof only.

This study was made to investigate the dose attenuation of fallout gamma radiation by various thicknesses of concrete roofs of buried fallout shelters as a function of time after a nuclear detonation. A spectrum of energies is used for the fallout source rather than a single average energy as has been done in previous studies. Dose attenuation factors are derived and presented as a function of the above parameters. The Office of Civil and Defense Mobilization recommends a two-week shelter-stay time in the event of a nuclear attack; therefore, also presented is an average dose attenuation factor for any fourteen-day stay time as a function of time of arrival of the fallout or of shelter-entry time, for various roof thicknesses.

INTRODUCTION

In this nuclear age, warfare and defense problems have become increasingly more scientific. A nuclear weapon explosion results in earth and bomb debris which is contaminated with radioactive fission products. This radioactive debris is known as residual radiation or fallout, and it constitutes a serious hazard to unsheltered personnel. It is necessary therefore to provide shelter from the harmful radiation.

Underground or buried shelters have a definite advantage over other types in resisting the effects of atomic weapons, especially fallout. The amount of protection received from an underground shelter is a function of the mass density of material in the shelter roof since the amount of radiation coming through the walls is negligible compared to that coming through the roof. This results in greater net protection than afforded by a surface shelter of equal cost.

If the size of the shelter is large, that is, not the small, single-family type, the roof can be approximated by an infinite concrete slab for acceptably precise mathematical determination of its shielding capabilities.

The purpose of this study is to investigate the dose attenuation factor for fallout gamma radiation as a function of time after detonation of a nuclear weapon for various thicknesses of infinite concrete slab shields. In addition, using the Office of Civil and Defense Mobilization criterion of a two-week stay time in fallout shelters, a factor has been calculated which will determine the dose received during that stay time as a function of the H + 1-hour dose rate, of the time of arrival of the fallout after detonation or of shelter entry time, and of the slab thickness of the shelter roof. An average dose attenuation factor for any fourteen-day shelter-stay time as a function of the above is also presented.

Previous work has been done by Chilton and Saunders[1] to determine the dose attenuation factor as a function of roof slab thickness by using an average energy of 1.0 mev for the fallout radiation. This study will to a great extent parallel the above work, but will use the gamma spectral data of Nelms and Cooper[2] for various times after fission to specify the energy of the fallout radiation.

PROBLEM CONSIDERATIONS

The geometrical situations investigated are shown in Figure 1. In Figure 1(a), it is assumed the fallout is evenly distributed on top of a smooth infinite plane surface. Two dose points, D_1 and D_2, are indicated. D_2 is the dose received at the standard 3-foot distance above a uniformly contaminated infinite plane. D_1 is the dose received at a vertical distance h beneath the contaminated plane with a varying thickness of material, t, in between the contaminated plane and the dose point D_1. In this study, concrete was the material considered, but earth could be used if the appropriate mass density equivalent is used.

It has been found that in the computation of the dose at D_1 the value of h does not greatly affect the result provided h is less than a mean free path in air and t is about 0.25 feet of concrete or greater. The area of interest in this study is for roof slabs with thicknesses equal to or greater than 0.25 feet; therefore, for convenience, h was arbitrarily chosen to be 3 feet. This choice was made so that when the same computation is made for $t = 0$, the dose calculated at D_1 would be numerically valid for the dose received at D_2.

A dose attenuation factor for the smooth plane case can now be defined as the ratio of the dose received in the open at a distance of 3 feet above a uniformly contaminated plane source to the dose received inside a buried shelter where the roof approximates a concrete slab shield. This smooth plane dose attenuation factor, AF_1, is equal to D_1/D_2.

In order to account for the roughness of terrain that would be encountered in practical cases, a method[3] suggested by the U. S. Naval Radiological Defense Laboratory in 1955 is used. As can be seen in Figure 1(b), the contamination is assumed to be uniformly distributed in the top one-half inch of soil under the infinite plane. The distance h is the vertical distance from the incremental segment of contamination to the dose-point D_3. The distance H is the distance from the top of the soil to dose-point D_3 and was assumed to be 3 feet in the calculation.

The dose attenuation factor for the rough-plane case, AF_2, is defined as D_1/D_3. (The concrete roof of the structure is not considered to be rough, even though the surrounding plane area of soil is so considered.)

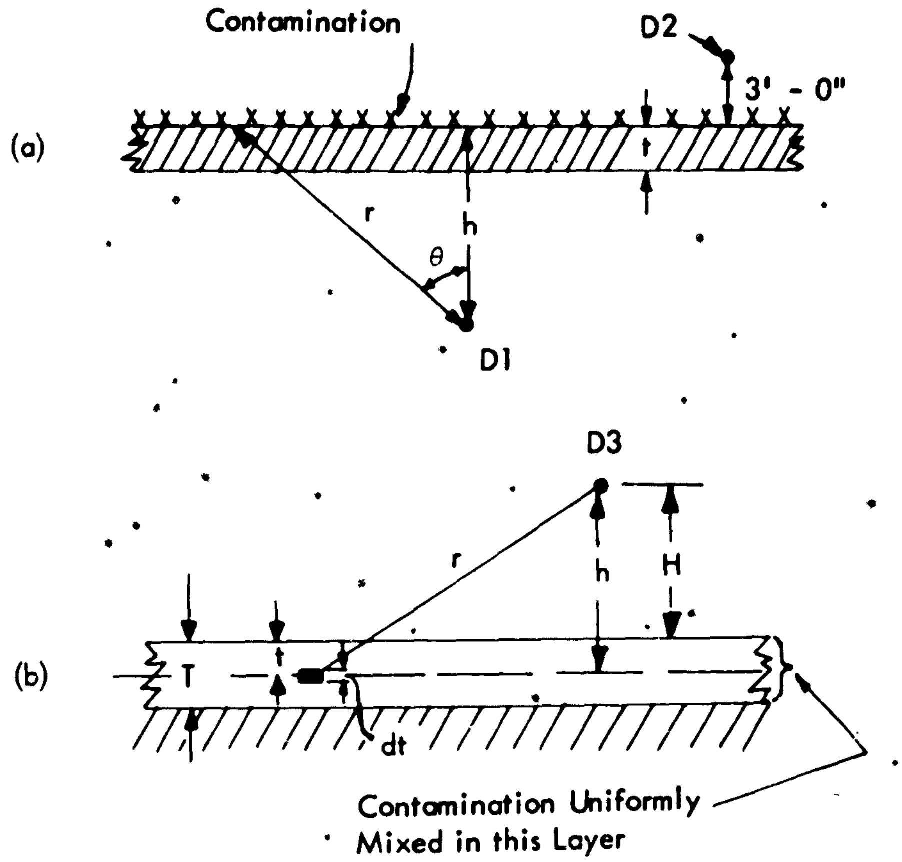


Figure 1. Geometric situations studied.

CALCULATIONS

The calculations used in this study for the doses at D_1, D_2, and D_3 are slight modifications of the calculations presented in the Chilton and Saunders study. Details of the derivations are presented in the Appendix. Only the three integrated dose equations used in the study will be presented here.

$$D_1 = \frac{K E_o \bar{\mu}_o}{2\rho} \left[-E_i(-\mu_1 h) + A_1 e^{-B_1 \mu_1 h} + A_2 e^{-B_2 \mu_1 h} \right] \qquad (1)$$

$$D_2 = \frac{K E_o \bar{\mu}_o}{2\rho} \left[-E_i(-\mu_a h) + A_1 e^{-B_1 \mu_a h} + A_2 e^{-B_2 \mu_a h} \right] \qquad (2)$$

$$D_3 = \frac{K E_o \bar{\mu}_o}{2\rho \mu_e T} \left\{ \left[-E_i(-\mu_3 H)\, \mu_3 H \right] \right.$$

$$- \left[-E_i(-\mu_a H)\, \mu_a H - e^{-\mu_a H} + e^{-\mu_3 H} \right]$$

$$+ \frac{A_1}{B_1} \left[e^{-B_1 \mu_a H} - e^{-B_1 \mu_3 H} \right]$$

$$\left. + \frac{A_2}{B_2} \left[e^{-B_2 \mu_a H} - e^{-B_2 \mu_3 H} \right] \right\} \qquad (3)$$

where: $\mu_1 = \mu_a + \frac{t}{h}(\mu_c - \mu_a)$

$\mu_3 = \mu_a + \mu_e \frac{T}{H}$

K = Photons/sec for each energy group specified by Nelms and Cooper[2]

E_o = The mean energy of the energy group at which all other energy dependent properties are evaluated, mev

$\bar{\mu}_o$ = Linear energy absorption coefficient of air, cm^{-1}

ρ = Density of air, gm/cc

μ_a = Linear total absorption coefficient of air (12.06×10^{-4} gm/cc), cm^{-1}

μ_e = Linear total absorption coefficient of earth (1.442 gm/cc), cm^{-1}

μ_c = Linear total absorption coefficient of concrete (2.357 gm/cc), cm^{-1}

$-E_i(-\mu X)$ = Exponential integral of form $\int_{\mu X}^{\infty} \frac{e^{-t}}{t}\, dt$

A_1, B_1, A_2, B_2 = Build-up factor coefficients of Berger and Spencer.[4]

The build-up factor is defined as the ratio of some measurable property of the photon beam (i.e., intensity, number of photons, energy flux, or biological dose), when the effects of all quanta are included, to that obtained when only the uncollided flux is considered. Many analytical functions have been derived to describe the dose build-up factor for all photon energies. In this study a biological dose build-up factor of the following form (suggested by Berger and Spencer[4]) is used:

$$B_r = 1 + A_1 B_1 \mu r e^{-(B_1-1)\mu r} + A_2 B_2 \mu r e^{-(B_2-1)\mu r} \qquad (4)$$

where A_1, A_2, B_1, B_2 are dimensionless coefficients and μr is the number of mean free paths of material. The coefficients A_1, B_1, A_2, and B_2 allow the empirical dose build-up factors of Berger[4] to fit the dose build-up factor data of Goldstein and Wilkins[5] for aluminum. This is also considered reasonably valid for concrete and earth.

RESULTS

The doses from the above equations were calculated on an IBM-705 computer, using the spectral data of Nelms and Cooper,[2] the air linear energy absorption coefficients provided by Berger,[4] and the linear total absorption coefficient data of

Gladys W. Grodstein[6] for each energy group. The sum of the doses received from each of the energy groups represents the dose received through a particular thickness of slab shield. Fallout spectra for 1.12 hours, 5.15 hours, 23.8 hours, 2.13 days, 4.57 days, 9.82 days, 21.1 days, 45.3 days, 97.3 days, and 208 days after fission were investigated. Data for these spectra are tabulated by Nelms and Cooper.[2]

Figure 2 is a presentation of the dose attenuation factor AF_1 plotted as a function of concrete shield thickness for the 1.12-hour, 23.8-hour, 4.57-day, 21.1-day, and 208-day spectra. It can be noted that the attenuation of the 21.1-day spectrum is definitely less than that of the 23.8-hour spectrum. On the other hand, on the basis of data provided by Miller, based on a spectrum identical to Nelms and Cooper[2] and plotted in Figure 3, it can be seen that the average energy per photon from fission products at 23.8 hours is greater than at 21.1 days. If the mean energy per photon is a good estimation of the penetration power of the radiation, then it would be expected that the attenuation of the 23.8-hour fallout spectrum would be less than that of the later 21.1 day spectrum. It is shown in Figure 2 that the opposite is true. This anomaly is discussed in the next section.

Figure 4 shows the attenuation factor for the rough-plane case, AF_2, plotted against slab thickness for the same spectra as AF_1. It was found that the only difference between the AF_2 and AF_1 curves is that the attenuation for the rough-plane source is less by a factor of about 1.6 at all times.

Figure 5 shows the attenuation factor AF_1 plotted as a function of time after fission for various slab thicknesses. It can be seen that, as the shield thickens, the attenuation factor varies more radically with time. It can be noted that the second maximum reached at about 500 hours is never greater than the initial maximum at 1.12 hours, for any of the thicknesses specified. Thus, the 1.12 hour fallout spectrum, which has been used in many shielding calculations to represent the fallout spectra in general, is still a conservative basis for use.

It is desirable to define a factor F as a function of the time of arrival of fallout or the shelter entry time (if fallout has already arrived) for various slab thicknesses, so that the factor F when multiplied by the dose rate at H + 1 hour will give the dose received by sheltered personnel in a fourteen-day stay-time after the burst. This factor F is derived by integrating the attenuation factor multiplied by the $t^{-1.2}$ decay scheme over various fourteen-day periods. If time is measured in hours, it can be seen that the fourteen-day stay dose is given by:

$$(\text{Dose})_{14\ \text{days}} = D_o\, F\,(t_1, T) = D_o \int_{t_1}^{t_1 + 336} t^{-1.2}\, AF\,(t_1, T)\, dt \qquad (5)$$

where: D_o = H + 1 hour dose rate in the open [at reference point 2 in Figure 1(a)]

AF = Attenuation factor at time t for concrete roof thickness T [Note: AF(t, 0) = 1]

t_1 = Time of arrival of fallout or start of 14-day stay-time if fallout has already arrived, hours

Figure 6 gives a plot of the factor F as a function of t_1. The factor does not vary in a simple mathematical way as a function of shelter entry time (t_1). This can be seen by the variation in the curves plotted for the 2- and 3-foot slab cases after about 40 hours.

An average attenuation factor can be plotted for any fourteen-day stay-time as a function of slab thickness and time of arrival of fallout or shelter-entry time. This average attenuation factor is determined by dividing the F factors for various slab thicknesses by the F factor for a 0.0-foot slab thickness at a particular time. The formula is:

$$AF_{ave} = \frac{\int_{t_1}^{t_1 + 336} t^{-1.2} \, AF\,(t, T)\, dt}{\int_{t_1}^{t_1 + 336} t^{-1.2} \, AF\,(t, 0)\, dt} \tag{6}$$

Figure 7 is a plot of AF_{ave} as a function of t_1 for various thicknesses of concrete roof shields. The dose that will be received in the open during any 14-day period after a nuclear explosion can be calculated by the following formula:

$$\text{Dose }(t_1)_{14 \text{ days (open)}} = \frac{D_o}{0.2} \left[\frac{1}{t_1^{\,0.2}} - \frac{1}{(t_1 + 336)^{0.2}} \right] \tag{7}$$

where D_o and t_1 are as defined before. The dose received inside the shelter for a 14-day stay-time would be:

$$\text{Dose}_{14 \text{ days (inside)}} = \text{Dose }(t_1)_{14 \text{ days (open)}} \, AF_{ave}\,(t_1, T) \tag{8}$$

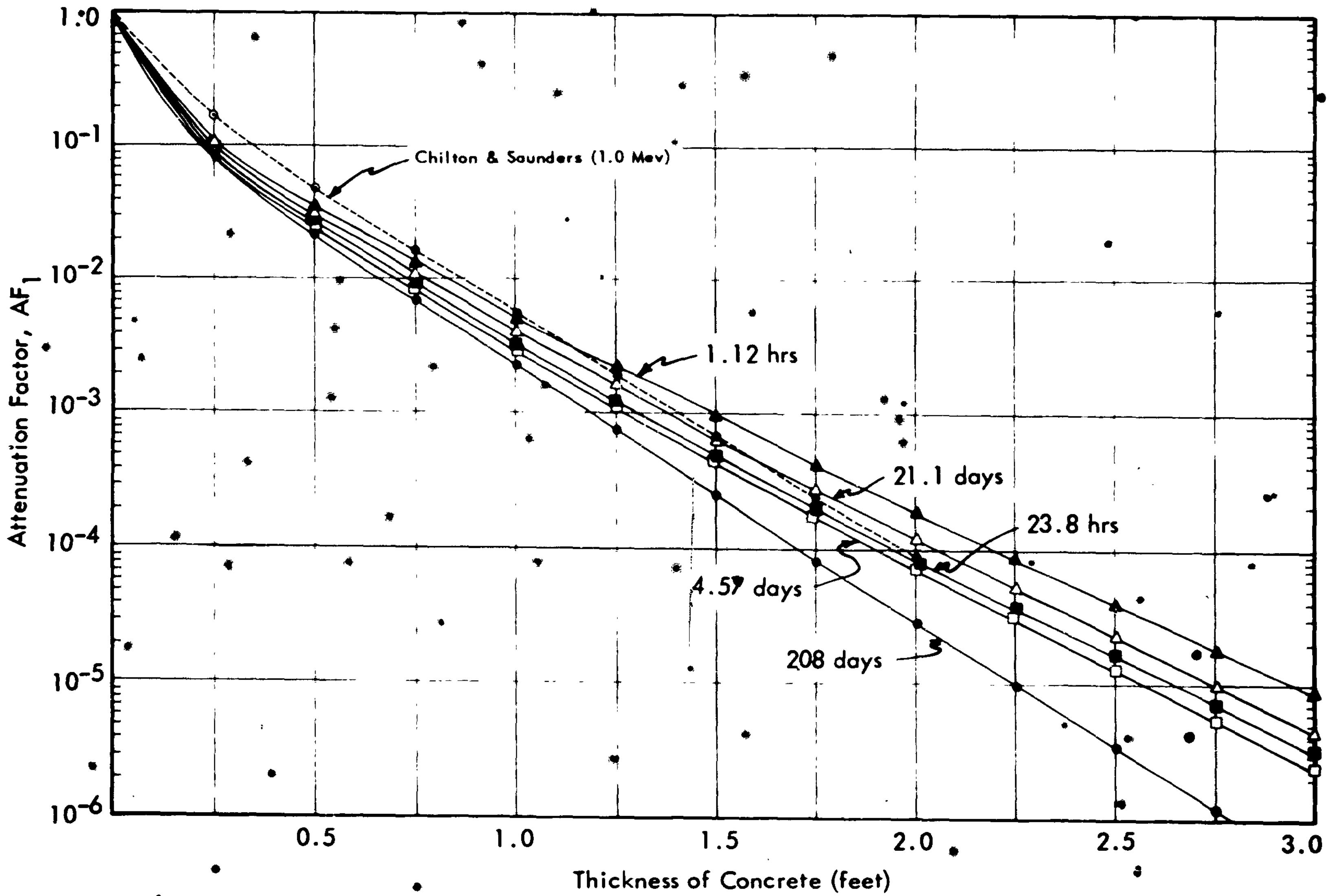


Figure 2. Attenuation factor versus concrete thickness for smooth isotropic plane source for various fission spectra.

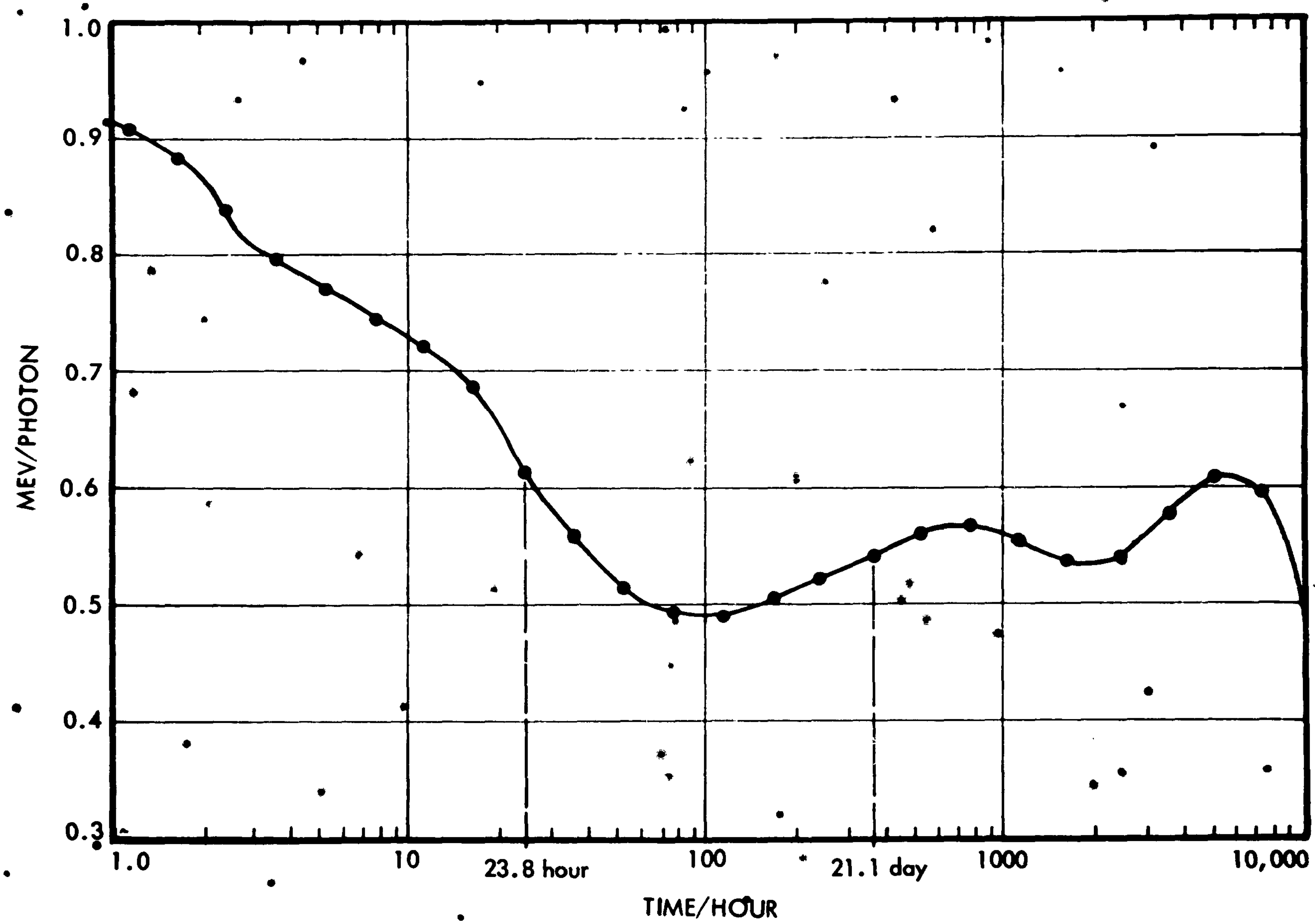


Figure 3. Mean energy per photon versus time after fission.

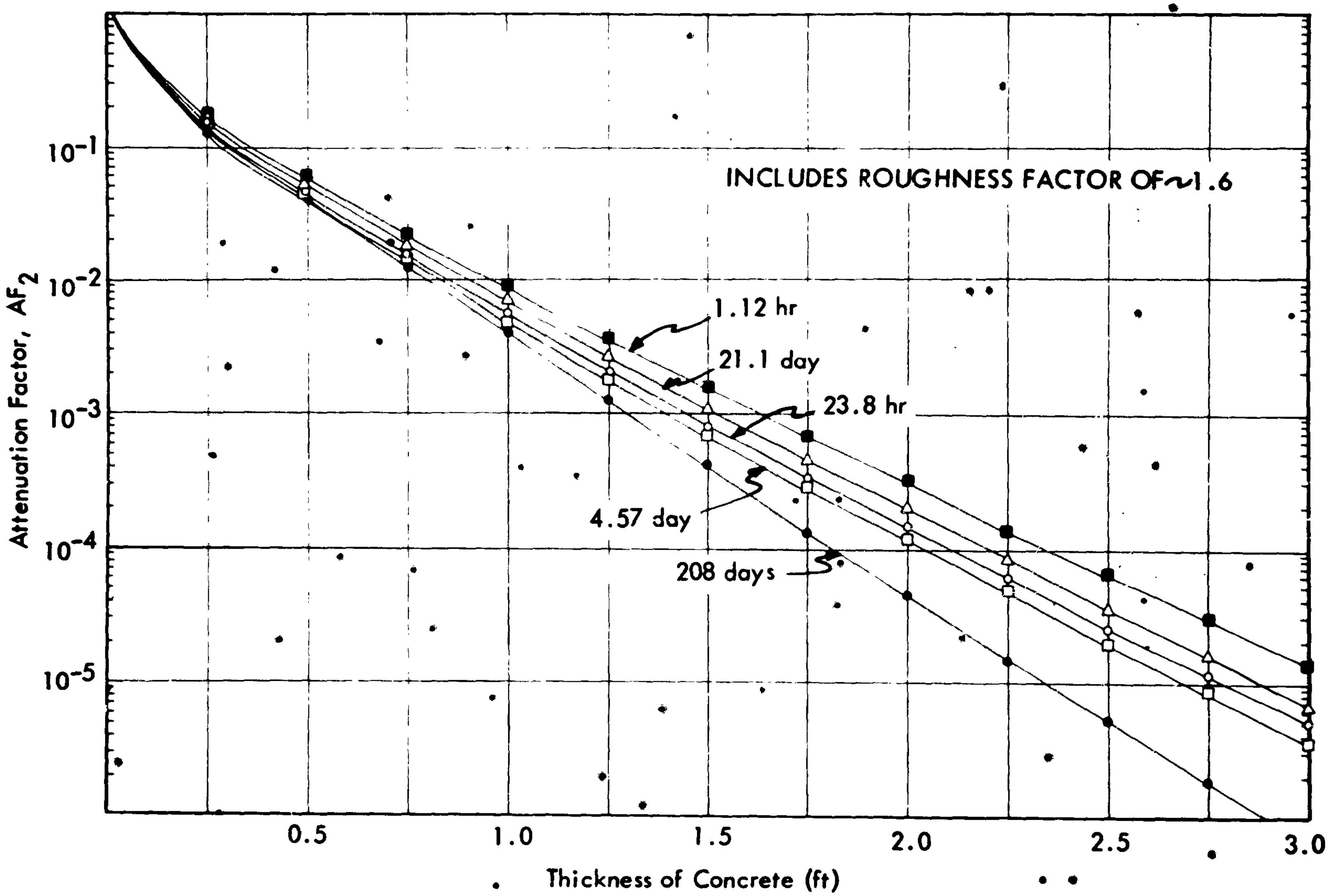


Figure 4. Attenuation factor versus concrete thickness for isotropic plane source of various fission spectra.

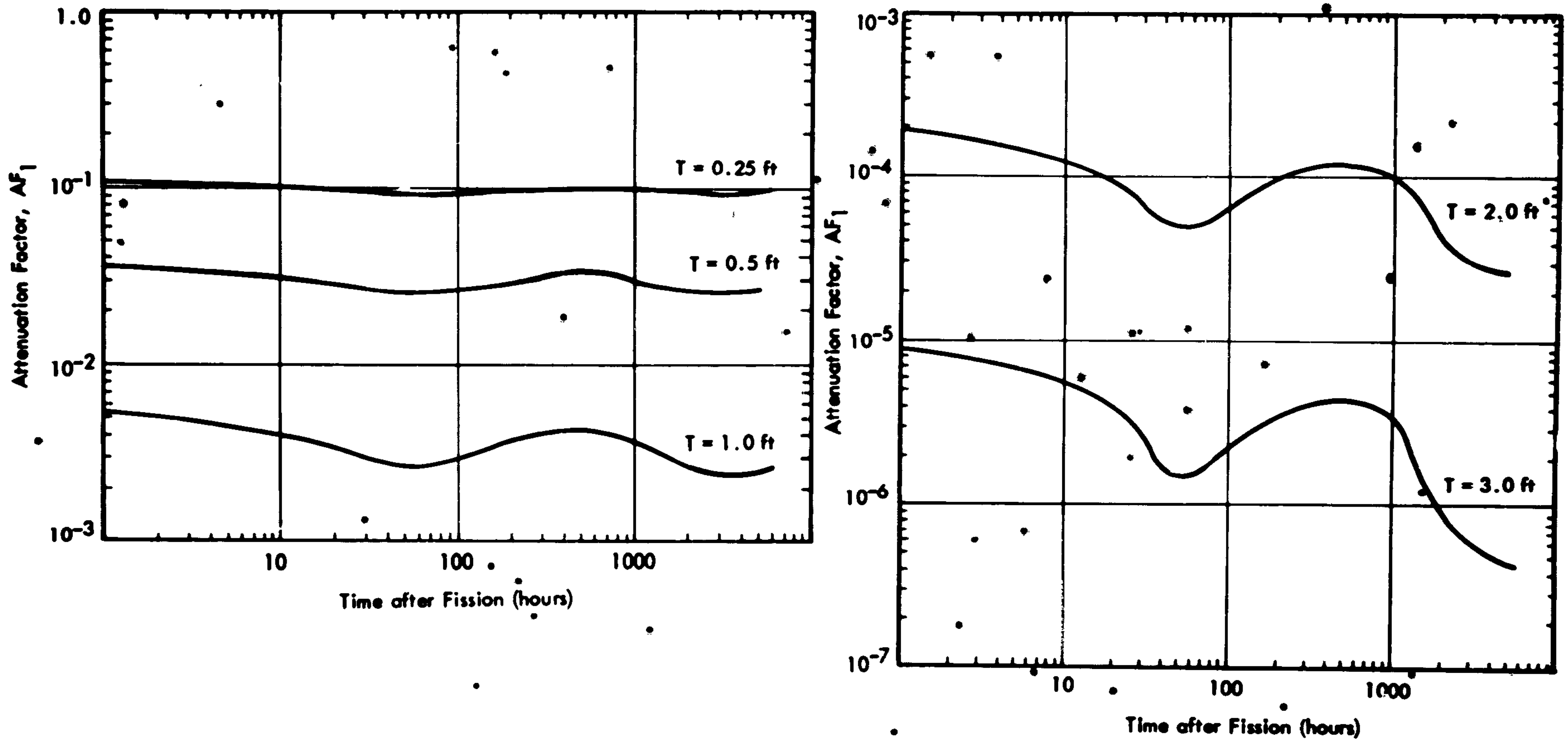
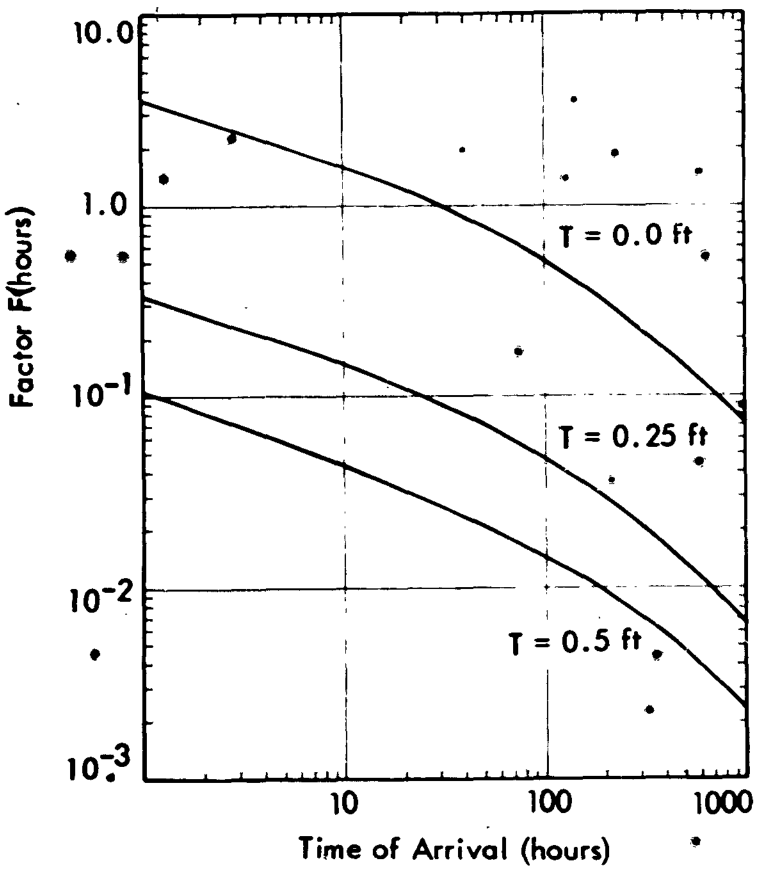


Figure 5. Attenuation factor versus time after fission for various thicknesses of concrete.



F x Dose Rate at H + 1 = Dose for 14 day stay time

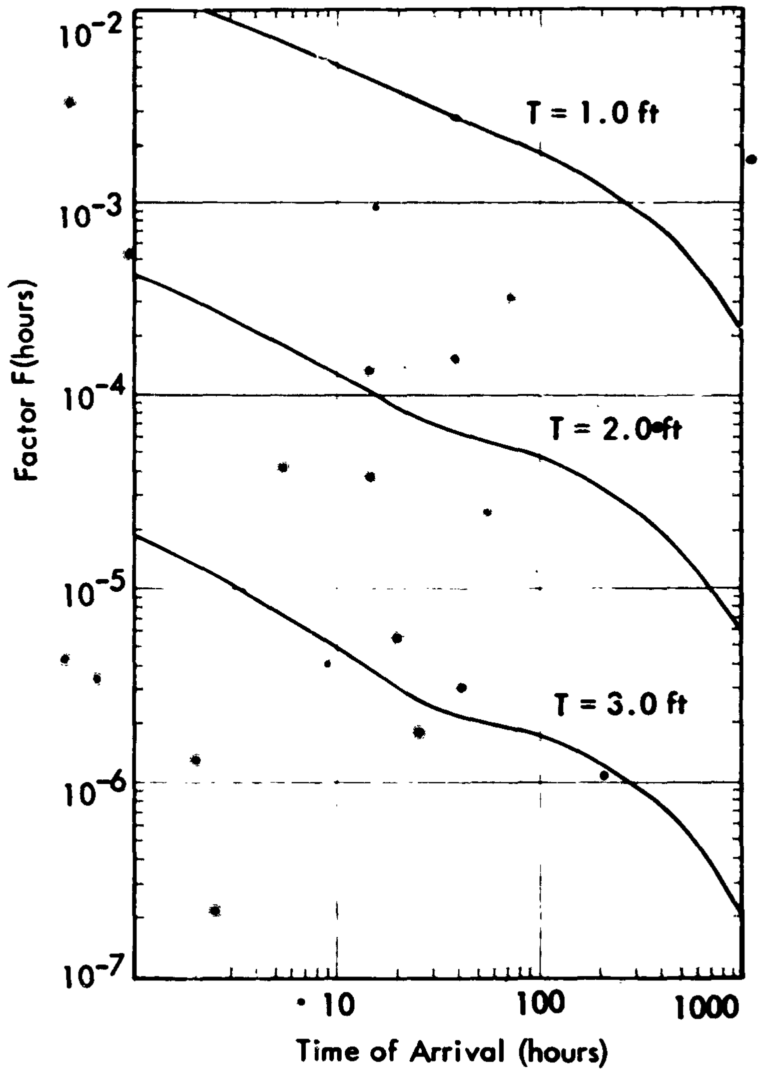


Figure 6. Factor F versus time of arrival of fallout for various thicknesses.

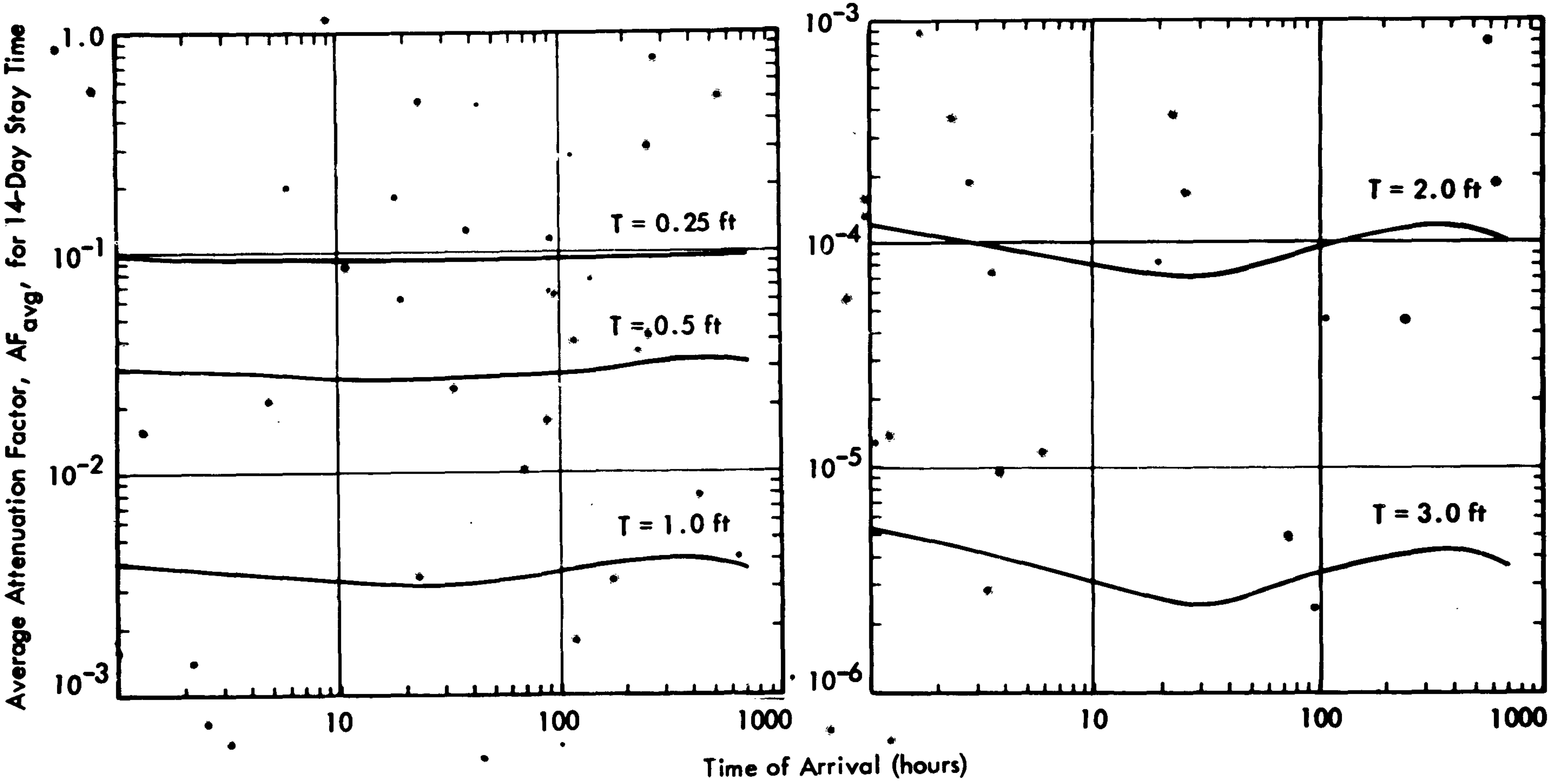


Figure 7. Average attenuation factor versus time of arrival of fallout for various concrete thicknesses.

DISCUSSION AND CONCLUSIONS

In Figure 2, the Chilton-Saunders results for 1-mev photons are plotted as a dotted line for comparison with the present results. It can be noted that the slope of the Chilton-Saunders curve closely follows that of the 208-day spectrum. This indicates that the 208-day fallout spectrum, after a few inches of concrete has filtered out the softer gamma rays, has penetration properties similar to monoenergetic gamma radiation with an energy of 1 mev. The 1.12-hour spectrum is obviously more penetrating than a 1-mev photon beam, after about the first foot of penetration.

As previously noted, the attenuation at 23.8 hours is greater than that at 21.1 days even though the mean energy per photon is greater at 23.8 hours. This is explained as follows: In the spectral dose calculations (Table I), it can be seen that the contribution of the spectrum to D_1 changes quite radically from 23.8 hours to 21.1 days. About 94.2 percent of the total contribution to D_1 for the 21.1-day spectrum came from radiation in the 1.47 - 2.95-mev initial energy range, while for the 23.8-hour spectrum, only 79.3 percent of the total dose comes from that same initial energy range and a greater contribution comes from photons of lower initial energies. Thus, even though the average energy of the photons may be greater for the 23.8-hour spectrum, the contribution to the dose shows a peak at a higher energy in the 21.1-day spectrum, which explains the lesser attenuation of the 21.1-day spectrum. After 21.1 days, the attenuation factor follows the expected path (Figure 5) but does not peak again around 208 days as would be expected from the Miller[7] data (Figure 3). This data indicates that the mean energy per photon is about the same at 208 days as it is for 23.8 hours. The explanation is similar to that given above.

In conclusion, it can be seen that at no initial entry time after 1.12 hours will a person in a shelter for fourteen days receive a greater dose than if fallout arrives at or before 1.12 hours after fission, and entry time is at 1.12 hours. This is obvious since there are no maxima greater than at 1.12 hours in the curves of Figure 7 for any of the thicknesses indicated.

If however an average attenuation factor for a particular fourteen-day stay-time is needed for accurately calculating the dose to be received, some care must be taken since the average attenuation factor may vary as much as a factor of two for stays commencing at some later time than 1.12 hours after fission.

Table I. Dose Contribution of Various Initial Energy Groups Through 2 Feet of Concrete for 23.8 Hours and 21.1 Days After Fission

	Percent Contribution to Total Dose			
Energy	23.8 Hour Spectrum Ref. 2		21.1 Day Spectrum Ref. 2	
0.0340	Negligible		Negligible	
0.0425	Negligible		Negligible	
0.0567	Negligible		Negligible	
0.0729	Negligible		Negligible	
0.1021	Negligible		Negligible	
0.1277	Negligible		Negligible	
0.1703	Negligible		Negligible	
0.2128	Negligible		Negligible	
0.2554	0.01		Negligible	
0.3193	0.01		0.02	
0.4257	Negligible		0.02	
0.5108	0.54		0.43	
0.6386	1.65		0.46	
0.8514	8.69		4.52	
0.0217	6.49		0.20	
1.2772	3.26		0.18	
1.7029	17.52	79.34	75.06	94.17
2.0435	25.09		1.45	
2.5545	36.73		17.66	

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3. U. S. Naval Radiological Defense Laboratory. TM-27, Gamma Radiations from Contaminated Planes and Slabs, by C. F. Ksanda, <u>et al</u>. San Francisco, 19 January 1955.

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Appendix

DERIVATION OF INTEGRATED DOSE EQUATIONS FOR A CONCRETE ROOF SLAB SHIELD COVERED WITH FALLOUT

CALCULATION OF THE DOSE RECEIVED AT D_1 [see Figure 1(a)]

The dose received at D_1 from an infinite contaminated smooth plane is:

$$D_1 = \frac{K\, E_o\, \bar{\mu}_o}{4\pi\rho} \int_{area} \frac{e^{-\mu_1 r}}{r^2}\, B_r\, dA \qquad (9)$$

where: K, E_o, $\bar{\mu}_o$ and ρ are as defined for Equation 1

B_r = Dose build-up factor

dA = An incremental area on the surface of the plane, cm^2

μ_1 = Effective linear absorption coefficient, cm^{-1}

It can be shown by similar triangles that $dA = 2\pi r dr$. Thus, Equation 7 becomes:

$$D_1 = \frac{K\, E_o\, \bar{\mu}_o}{2\rho} \int_{r=h}^{\infty} e^{-\mu_1 r}\, B_r \frac{dr}{r} \qquad (10)$$

The effective linear absorption coefficient, μ_1, takes into consideration the absorption of the air and the concrete slab. Therefore, $\mu_1 r$ can be expressed as:

$$\mu_1 r = \mu_a (h - t) \sec\theta + \mu_e\, t \sec\theta \qquad (11)$$

where μ_a and μ_e are as defined for Equation 1, and h, t, and θ as shown in Figure 1(a).

Since: $r = h \sec\theta$

then: $$\mu_1 = \mu_a + (\mu_e - \mu_a)\frac{t}{h} \qquad (12)$$

A dose build-up factor will be used as recommended by Berger and Spencer:[4]

$$B_r = 1 + A_1 B_1 \mu_1 r\, e^{-(B_1-1)\mu_1 r} + A_2 B_2 \mu_1 r\, e^{-(B_2-1)\mu_1 r} \qquad (13)$$

where: A_1, A_2, B_1, B_2 are dimensionless coefficients.

Substituting Equation 13 into Equation 10, we have:

$$\dot{D}_1 = \frac{K E_o \bar{\mu}_o}{2\rho}\left[\int_{r=h}^{\infty} e^{-\mu_1 r}\frac{dr}{r} + \int_{r=h}^{\infty} A_1 B_1 \mu_1 r\, e^{-B_1\mu_1 r}\frac{dr}{r} + \int_{r=h}^{\infty} A_2 B_2 \mu_1 r\, e^{-B_2\mu_1 r}\frac{dr}{r}\right] \qquad (14)$$

Looking at the first integral of Equation 14, it can be seen that it is in the form of the exponential integral.

$$\int_{r=h}^{\infty} e^{-\mu_1 r}\frac{d(\mu_1 r)}{\mu_1 r} = -E_i(-\mu_1 h) \qquad (15)$$

In computing the second integral

since: $$\frac{d}{dr}\left(A_1 e^{-B_1\mu_1 r}\right) = A_1 e^{-B_1\mu_1 r}(-B_1\mu_1)$$
$$= -A_1 B_1 \mu_1 e^{-B_1\mu_1 r}$$

then: $$\int_{r=h}^{\infty} A_1 B_1 \mu_1 r e^{-B_1 \mu_1 r} \frac{dr}{r} = -A_1 e^{-B_1 \mu_1 r} \Big|_h^{\infty} = A_1 e^{-B_1 \mu_1 h} \quad (16)$$

Similarly for the third integral:

$$\int_{r=h}^{\infty} A_2 B_2 \mu_1 r e^{-B_2 \mu_1 r} \frac{dr}{r} = A_2 e^{-B_2 \mu_1 h} \quad (17)$$

Combining Equations 15, 16, and 17, we have:

$$D_1 = \frac{K E_o \bar{\mu}_o}{2\rho} \left[-E_i(-\mu_1 h) + A_1 e^{-B_1 \mu_1 h} + A_2 e^{-B_2 \mu_1 h} \right] \quad (1)$$

CALCULATION OF THE DOSE RECEIVED AT D_2

The equation for the dose received at D_2 is derived in the same way as dose D_1 except that only the absorption by the air need be considered. Thus $\mu_1 = \mu_a$. The standard 3-foot height above the contaminated plane was selected (see Figure 1), but is represented in the equation by h.

$$D_2 = \frac{K E_o \bar{\mu}_o}{2\rho} \left[-E_i(-\mu_a h) + A_1 e^{-B_1 \mu_a h} + A_2 e^{-B_2 \mu_a h} \right] \quad (2)$$

CALCULATION OF THE DOSE RECEIVED AT D_3

The dose at D_3 is due to the contamination mixed uniformly in a thin layer at the surface of the plane as shown in Figure 1(b). This method is used to approximate surface roughness. The general equation for the dose at D_3 is:

$$D_3 = \frac{K E_o \bar{\mu}_o}{4\pi\rho} \int_{t=0}^{T} \int_{area} B_r e^{-\mu_1 r} dA \frac{dt}{T} \quad (18)$$

where: K, E_o, $\bar{\mu}_o$, ρ, B_r, and dA are as defined previously

t, dt, and T are as shown in Figure 1(b)

μ_1 = An effective total linear absorption coefficient

From Figure 1(b), it can be seen that

$$H = h - t$$

$$r = h \sec\theta$$

If: $$\mu_1 r = \mu_e t \sec\theta - \mu_a (h - t) \sec\theta,$$

then: $$\mu_1 \doteq \mu_a \pm (\mu_e - \mu_a) \frac{t}{h} \tag{19}$$

where: μ_e and μ_a are as defined for Equation 3

θ = Angle between r and h

Since: dA = $2\pi r\,dr$, Equation 18 becomes

$$D_3 = \frac{K E_o \bar{\mu}_o}{2 \rho T} \int_{t=0}^{T} \int_{r=h}^{\infty} B_r e^{-\mu_1 r} \frac{dr}{r} dt \tag{20}$$

Using the build-up factor, Equation 13, and substituting into Equation 20, gives:

$$D_3 = \frac{K E_o \bar{\mu}_o}{2 \rho T} \left[\int_{t=0}^{T} \int_{r=h}^{\infty} e^{-\mu_1 r} \frac{dr}{r} dt + \int_{t=0}^{T} \int_{r=h}^{\infty} A_1 B_1 \mu_1 r\, e^{-B_1 \mu_1 r} \frac{dr}{r} dt + \int_{t=0}^{T} \int_{r=h}^{\infty} A_2 B_2 \mu_1 r\, e^{-B_2 \mu_1 r} \frac{dr}{r} dt \right] \tag{21}$$

Computation of the first integral:

$$\int_{t=0}^{T} \int_{r=h}^{\infty} e^{-\mu_1 r} \frac{dr}{r} dt = \int_{t=0}^{T} -E_i(-\mu_1 h)\, dt \qquad (22)$$

Using integration by parts of the form: $\int u\, dv = uv - \int v\, du$

$$\int_{t=0}^{T} -E_i(-\mu_1 h)\, dt = \left[-E_i(-\mu_1 h)\; t \right]_0^T + \int_{t=0}^{T} t \frac{d}{dt} \left[E_i(-\mu_1 h) \right] dt \qquad (23)$$

But: $$\mu_1 h = \mu_a H + \mu_e t$$

$$\frac{d}{dt}(\mu_1 h) = \mu_e$$

$$d(\mu_1 h) = \mu_e\, dt$$

$$dt = \frac{d(\mu_1 h)}{\mu_e}$$

Also when: $$t = 0, \quad \mu_1 h = \mu_a H$$

$$t = T, \quad \mu_1 h = \mu_a H + \mu_e T$$

Since: $$E_i(-\mu_1 h) = \int \frac{e^{-\mu_1 h}}{(-\mu_1 h)}\, d(-\mu_1 h)$$

$$\frac{d}{dt}\left[E_i(-\mu_1 h) \right] = \frac{d\,[E_i(\mu_1 h)]}{d(-\mu_1 h)} \frac{d}{dt}(-\mu_1 h)$$

$$\frac{d}{dt}\left[E_i(-\mu_1 h)\right] = \frac{-e^{-\mu_1 h}}{\mu_1 h}(-\mu_e) = \frac{\mu_e}{\mu_1 h} e^{-\mu_1 h} \tag{24}$$

therefore: $$\int_{t=0}^{T} -E_i(-\mu_1 h)\, dt = -E_i(-\mu_a H - \mu_e T)\, T + \int_0^T \frac{\mu_e t}{\mu_1 h} e^{-\mu_1 h}\, dt$$

$$\int_{t=0}^{T} -E_i(-\mu_1 h)\, dt = -E_i(-\mu_a H - \mu_e T)\, T + \int_0^T e^{-\mu_1 h}\, dt - \int_0^T \frac{\mu_a H}{\mu_1 h} e^{-\mu_1 h}\, dt$$

$$= -E_i(-\mu_a H - \mu_e T)\, T + \frac{1}{\mu_e}\int_{\mu_a H}^{\mu_a H + \mu_e T} e^{-\mu_1 h}\, d(\mu_1 h)$$

$$- \frac{\mu_a H}{\mu_e}\int_{\mu_a H}^{\mu_a H + \mu_e T} \frac{e^{-\mu_1 h}}{\mu_1 h}\, d(\mu_1 h)$$

$$= \left[-E_i(-\mu_a H - \mu_e T)\, T\right] - \frac{1}{\mu_e}\left[e^{-\mu_1 h}\right|_{\mu_a H}^{\mu_a H + \mu_e T}$$

$$- \frac{\mu_a H}{\mu_e}\left[E_i(-\mu_1 h)\right|_{\mu_a H}^{\mu_a H + \mu_e T}$$

$$= \left[-E_i(-\mu_a H - \mu_e T)\, T\right] - \frac{1}{\mu_e} e^{-\mu_a H - \mu_e T} + \frac{1}{\mu_e} e^{-\mu_a H}$$

$$- \frac{\mu_a H}{\mu_e}\left[E_i(-\mu_a H - \mu_e T)\right] + \frac{\mu_a H}{\mu_e}\left[E_i(-\mu_a H)\right]. \tag{25}$$

To simplify, let $\mu_3 H = \mu_a H + \mu_e T$; and since $T = (\mu_3 H - \mu_a H)/\mu_e$, Equation 25 becomes:

$$\int_{t=0}^{T} -E_i(-\mu_1 h)\, dt = \frac{1}{\mu_e} \left\{ -E_i(-\mu_3 H)\, \mu_3 H \right.$$

$$\left. - \left[-E_i(-\mu_a H)\, \mu_a H - e^{-\mu_a H} + e^{-\mu_3 H} \right] \right\} \tag{26}$$

Computation of the second integral:

$$\int_{t=0}^{T} \int_{r=h}^{\infty} A_1 B_1 \mu_1 r\, e^{-B_1 \mu_1 r} \frac{dr}{r}\, dt = \int_{t=0}^{T} A_1 e^{-B_1 \mu_1 h}\, dt \tag{27}$$

But: $\mu_1 h = \mu_a H + \mu_e T$

$$\int_{t=0}^{T} A_1 e^{-B_1 \mu_1 h}\, dt = \int_{t=0}^{T} A_1 e^{-B_1 (\mu_a H + \mu_e t)}\, dt$$

$$= A_1 e^{-B_1 \mu_a h} \int_{t=0}^{T} e^{-B_1 \mu_e t}\, dt$$

$$= A_1 e^{-B_1 \mu_a H} \left[- \frac{e^{-B_1 \mu_e t}}{B_1 \mu_e} \right|_0^T$$

$$= \frac{A_1}{B_1 \mu_e} e^{-B_1 \mu_a H} \left[1 - e^{-B_1 \mu_e T} \right] \tag{28}$$

Since $T = \mu_3 H - \mu_a H/\mu_e$, then Equation 28 becomes:

$$\int_{t=0}^{T} A_1 e^{-B_1 \mu_1 h} dt = \frac{A_1}{\mu_e B_1} \left(e^{-B_1 \mu_a H} - e^{-B_1 \mu_3 H} \right) \tag{29}$$

Computation of the third integral:

$$\int_{t=0}^{T} \int_{r=h}^{\infty} A_2 B_2 \mu_1 r\, e^{-B_2 \mu_1 r} \frac{dr}{r} dt = \frac{A_2}{\mu_e B_2} \left(e^{-B_2 \mu_a H} - e^{-B_2 \mu_3 H} \right) \tag{30}$$

Combining Equations 26, 29, and 30, we have as the solution to Equation 18:

$$\begin{aligned} D_3 = \frac{K E_o \bar{\mu}_o}{2 \rho \mu_e T} & \Big(-E_i(-\mu_3 H)\, \mu_3 H \\ & - \left[-E_i(-\mu_a H)\, \mu_a H - e^{-\mu_a H} + e^{-\mu_3 H} \right] \\ & + \frac{A_1}{B_1} \left[e^{-B_1 \mu_a H} - e^{-B_1 \mu_3 H} \right] \\ & + \frac{A_2}{B_2} \left[e^{-B_2 \mu_a H} - e^{-B_2 \mu_3 H} \right] \Big) \end{aligned} \tag{3}$$

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